MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER			
U. S. Army Research Office		DAAG29-84-K-0202			

8c. ADDRESS *(City, State, and ZIP Code)*	10. SOURCE OF FUNDING NUMBERS			
P. O. Box 12211 Research Triangle Park, NC 27709-2211	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
Development & Organization of Neural Networks

12. PERSONAL AUTHOR(S)
Leon N. Cooper

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Final	FROM 10/1/84 TO 2/31/87	January 1988	19

16. SUPPLEMENTARY NOTATION
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	Neural Networks, Cortex, Cell Evolution, Neurons

Our investigation of the evolution of a cell in this mean field
network indicates that many of the results on the existence and
stability of fixed points that have been obtained previously in
the single cell theory are successfully generalized here. In
addition, we have been able to make explicit further statements
concerning the independent effects of excitatory and inhibitory
neurons on selectivity and ocular dominance.

22000-LS

FINAL REPORT
TWENTY COPIES REQUIRED

1.   ARO PROPOSAL NUMBER: 22000-LS

2.   PERIOD COVERED BY REPORT: 1 October 1984 – 31 December 1987

3.   TITLE OF PROPOSAL: Development & Organization of Neural Networks

4.   CONTRACT OR GRANT NUMBER: DAAG29-84-K-0202

5.   NAME OF INSTITUTION: Brown University

6.   AUTHORS OF REPORT: Professor Leon N Cooper

7.   LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING
       THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

Distributed Memory, Cooper, L. N., in Encyclopedia of Neurosciences, Vol. II, ed. G.
Adelman pp. 633-634, Birkhauser, Boston, 1987; also ARO Technical Report, March 13,
1985.

Cortical Plasticity: Theoretical Analysis, Experimental Results, in Imprinting and Cortical
Plasticity, ed. J. P. Rauschecker and P. Marler, John Wiley & Sons, N. Y., 1987, also ARO
Technical Report, July 10, 1985.

Local and Global Factors in Learning, to be published in Brain Structure, Learning and
Memory, ed. J. Davis, R.W. Newburgh, and E. Wegmen, by AAAS, also ARO Technical
Report, November 6, 1985.

Theory of an immune system retrovirus, Cooper, L. N, Proc. Natl. Acad. Sci., Vol. 83,
pp.9159-9163, December 1986.

Connectivity in Neural Networks, Cooper, L. N, to be published in the Proceedings of
the Copenhagen Conference on Computer Simulation in Brain Research.

Mean Field Theory of a Neural Network, Cooper, L. N, Scofield, C. L., to be
published in Proc. Natl. Acad. Sci., also ARO Technical Report, January , 1988.

Storing and Retrieving Data in a Parallel Distributed Memory System, Potter, T. W.,
Dissertation, also ARO Technical Report, June 9, 1987.

The Hopfield Model and Beyond, Bachmann, C. M., ARO Technical Report , December
15, 1986.

A Relaxation Model for Memory with High Storage Density, Bachmann, C. M., Cooper, L.
N, Dembo, A., and Zeitouni, O., Proc. Natl. Acad. Sci., Vol. 84, pp. 7529-7531,
November, 1987, also ARO Technical Report, June 22, 1987.

General Potential Surfaces and Neural Networks, Dembo, A, Zeitouni, O., to be published
in Phys. Rev. A , also ARO Technical Report, June 24, 1987.

Analysis of Immune System Retrovirus Equations, Intrator, N., Deocampo, G. P., Cooper,
L. N., (to be published in the Conference Record of The Santa Fe Institute, July 1987).

Generalization and the Backward Propagation Neural Network, Bachmann, C. M., ARO
Technical Report , January, 1988.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING
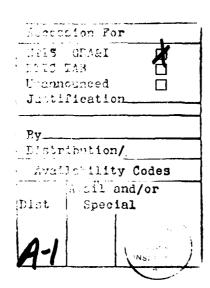   THIS REPORTING PERIOD:

Scientific personnel supported:

Leon N Cooper
Walter Freiberger
Charles Bachmann
Christopher Bray
Eugene Clothiaux
Nathan Intrator
Bradley Seebach
Gregory Deocampo

Degrees Awarded:

Charles M. Bachmann, Sc. M.
Eugene E. Clothiaux, Sc. M.
 Terry W. Potter, Ph. D.

Leon N Cooper
Department of Physics
Center for Neural Science
Brown University
Providence, R. I. 02912

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DTIC TAB	☐
Unannounced	☐
Justification	

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During the period covered by this grant, January 1,1985 - December 31, 1987, we have made substantial progress in our analysis of the development and organization of neural networks in a number of related areas.

Previously, we had proposed a single cell theory for the development of selectivity and ocular dominance in a neural network.[1][2] During the contract period, this theory has been generalized to incorporate more realistic neural networks that approximate the actual anatomy of small regions of cortex. In particular, we have analyzed a network consisting of excitatory and inhibitory cells, both of which may receive information from LGN. These two cortical cell types then interact through intracortical connections that are either excitatory or inhibitory. Our investigation of the evolution of a cell in this mean field network indicates that many of the results on the existence and stability of fixed points that have been obtained previously in the single cell theory are successfully generalized here. In addition, we have been able to make explicit further statements concerning the independent effects of excitatory and inhibitory neurons on selectivity and ocular dominance. For example, shutting off inhibitory cells lessens selectivity and alters ocular dominance (masked synapses). These inhibitory cells may be selective, but there is no theoretical necessity that they be so. Further, the intracortical inhibitory synapses do not have to be very responsive to visual experience. Most of the learning process can occur among the excitatory LGN-cortical synapses. The theoretical results are compared with experiment in completed and continuing work. [3][4][5][6]

Another area in which we have made substantial progress is the analysis of relaxation mechanisms in neural network. We have investigated the improvement of the storage efficiencey in the Hopfield model. The original model was capable of accurate storage and retrieval, with some error correction, for up to 0.1N stored states, where N is the number of neurons. With "unlearning", it is possible for the system to recall up to N stored states with some error correcting ability.[7] We have studied a variation of Hopfield's "unlearning" which is able to achieve storage and retrieval of well above N patterns but with little error-correcting capability; this variation bears a resemblance to the Widrow-Hoff error correcting procedure. [8] Our theoretical analysis of this scheme showed that the method was equivalent

to an "effective orthogonalization"; further, the limitations of this approach were analyzed in terms of an attractor signal and noise degradation due to such causes as the interaction of the system state with other stored states.[9]

Our analysis of the Hopfield Model led us to examine the general requirements for storage systems which have high capacity as well as good error-correcting capability. This has led us to propose an alternative relaxation procedure for a High Density Storage Model. The model incorporates an N-dimensional generalized coulombic potential with essentially inifinte storage; well-defined domains of attraction can be specified for the stored states, enabling categorization (generalization) of input states which have not been stored in the system.[10][11]

Like Neural circuits, the immune system network can learn and remember. The retrovirus HTLVIII/LAV which has been implicated as the agent responsible for the acquired immune deficiency syndrome(AIDS) attacks T_4(helper) cells of the immune system. We have shown that remarkable interactions with other infections as well as strong virus concentration dependence are general properties of ISRV. These theoretical results have been compared with experimental facts.[12] In addition, our theoretical model has been expanded to include some of the latest clinical results.[13]

The capacity of model neural networks to generalize from a partial set of information is an area of much current interest. The ability to categorize input, to make generalizations based on a limited set of information, is one of the hallmarks of higher cognitive processes. In our research in the recent past, we have undertaken an investigation of the recall and generalization capabilities of a number of neural models of current interest.

In this context, we have studied the Backward Propagation of Error Model first proposed by Rummelhart (1986). We have found that the model is capable of generalizing reasonably well in continous spaces where the decision boundaries are nonlinear and decision spaces may not be simply-connected(strong topology). As a paradigm, we have considered the problem of learning to distinguish the two regions enclosed by two concentric circles: the outer annulus, with target ouput of 1, and

the inner disk, with target output of 0. In simulations of this problem using the Backward Propagation Network, we have found that after training with randomly selected patterns in the two regions, the generalization curve of output versus radius approaches that of the ideal step-function, provided a sufficient number of patterns is used and provided that we do not saturate the network with too many training patterns.

In contrast, for a difficult problem on a lattice such as the parity problem with highly discontinous decision boundaries, patterns which are not used for training will generally not be correctly identified. In fact, the network will identify them as the state of opposite parity. Our analysis of continous space problems as described above, suggests in this instance that the system may be trying to generalize based on the nearest available information in the continous space sense, which in the case of the parity problem, where nearest neighbor states have opposite parity, leads to the misidentification.

Currently, we are exploring ways to modify the original Backward Propagation alogrithm so that it will be useful for generalization problems like that of parity, where generalization in the continuous-space sense, that is, assigning an output that mimics that of the nearest data point, is not an adequate solution. A number of possibilities are being investigated. Additional symmetry-sorting terms added to the Backward Propagation energy functional may prove useful in developing networks which can handle generalization tasks like parity. Another possibility is to present the data to the network in such a way that it is forced to satisfy the constraints of more than one pattern at the same time; the original Backward Propagation algorithm examines only one pattern at a time. In this context, additional symmetry-sorting energy terms may be also quite useful.[14]

[1]Theory for the Development of Neuron Selectivity: Orientation Specificity and Binocular Interaction in Visual Cortex, Bienenstock, E. L., Cooper, L. N, and Munro, P., Journal of Neuroscience 2 32-48 (1982).

[2]Distributed Memory, Cooper, L. N., in Encyclopedia of Neurosciences, Vol. II, ed. G. Adelman pp. 633-634, Birkhauser, Boston, 1987; also ARO Technical Report, March 13, 1985.

[3]Cortical Plasticity: Theoretical Analysis, Experimental Results, in Imprinting and Cortical Plasticity, ed. J. P. Rauschecker and P. Marler, John Wiley & Sons, N. Y., 1987, also ARO Technical Report, July 10, 1985.

[4]Local and Global Factors in Learning, to be published in Brain Structure, Learning and Memory, ed. J. Davis, R.W. Newburgh, and E. Wegmen, by AAAS, also ARO Technical Report, November 6, 1985.

[5]Mean Field Theory of a Neural Network, Cooper, L. N, Scofield, C. L., to be published in Proc. Natl. Acad. Sci., also ARO Technical Report, January, 1988.

[6]Connectivity in Neural Networks, Cooper, L. N, to be published in the Proceedings of the Copenhagen Conference on Computer Simulation in Brain Research.

[7]Storing and Retrieving Data in a Parallel Distributed Memory System, Potter, T. W., Dissertation and ARO Technical Report, June 9, 1987.

[8]op. cit.

[9]The Hopfield Model and Beyond, Bachmann, C. M., ARO Technical Report, December 15, 1986.

[10]A Relaxation Model for Memory with High Storage Density, Bachmann, C. M., Cooper, L. N, Dembo, A., and Zeitouni, O., Proc. Natl. Acad. Sci., Vol. 84, pp. 7529-7531, November, 1987, also ARO Technical Report, June 22, 1987.

[11]General Potential Surfaces and Neural Networks, Dembo, A, Zeitouni, O., to be published in Phys. Rev. A, also ARO Technical Report, June 24, 1987.

[12]Theory of an immune system retrovirus, Cooper, L. N, Proc. Natl. Acad. Sci., Vol. 83, pp.9159-9163, December 1986.

[13]Analysis of Immune System Retrovirus Equations, Intrator, N., Deocampo, G. P., Cooper, L. N., (to be published in the Conference Record of The Santa Fe Institute, July 1987).

[14]Generalization and the Backward Propagation Neural Network, Bachmann, C. M., ARO Technical Report, January, 1988.

Distributed Memory

Abstract

An account is given of the biological basis for and the elementary

properties of distributed memory. It is shown how a neural network

can be constructed to contain such a memory. Also discussed are

problems of address and recall of stored items, as well as the

possible sites of storage of short and long-term memory.

<u>Cortical Plasticity: Theoretical Analysis, Experimental Results</u>

<u>Abstract</u>

An account is given of a theory of and experimental results on development and modification of selectivity and ocular dominance in visual cortex. The single cell theory is generalized to be applicable to a neural network. Also discussed, in the context of the theoretical ideas, are experiments on the modifiability of inhibitory cells and on possible candidates for global controllers of learning.

Local and Global Factors in Learning

Abstract

Recent progress in the interaction of theoretical ideas and

experimental results that relate to learning and memory is discussed.

Consideration is given, in particular, to the effects of the neuro-

transmitters GABA, Norepinephrine and Acetylcholine on the develop-

ment of circuitry in visual cortex.

Theory of an Immune System Retrovirus

Abstract

Like neural circuits, the immune system network can learn and re-
member. The retrovirus HTLVIII/LAV which has been implicated as
the agent responsible for the acquired immune deficiency syn-
drome (AIDS) attacks T_4(helper) cells of the immune system. In
this paper, we contrast the growth of a 'normal' virus with what
we call an Immune System Retrovirus (ISRV): a retrovirus that
attacks T_4(helper) cells of the immune system. We show that
remarkable interactions with other infections as well as strong
virus concentration dependence are general properties of ISRV.
These ideas are compared with some known experimental facts.

Connectivity in Neural Networks

ABSTRACT

A single cell theory for the development of selectivity and ocular
dominance in visual cortex has been generalized to incorporate more
realistic neural networks that approximate the actual anatomy of small
regions of cortex. In particular we have analyzed a network consisting
of excitatory and inhibitory cells, both of which may receive informa-
tion from LGN. These.two cortical cell types then interact through
intracortical connections that are either excitatory or inhibitory.
Our investigation of the evolution of a cell in this mean field network
indicates that many of the results on existence and stability of fixed
points that have been obtained previously in the single cell theory can
be successfully generalized here. We can, in addition, make explicit
further statements concerning the independent effects of excitatory and
inhibitory neurons on selectivity and ocular dominance. For example,
shutting off inhibitory cells lessens selectivity and alters ocular
dominance (masked synapses). These inhibitory cells may be selective
but there is no theoretical necessity that they be so. Further the
intracortical inhibitory synapses do not have to be very responsive to
visual experience. Most of the learning process can occur among the
excitatory LGN-cortical synapses. Some of these theoretical ideas are
compared with experimental results.

Mean Field Theory of a Neural Network

(Visual Cortex/Synaptic Modification)
Leon N Cooper and Christopher L. Scofield*
Center for Neural Science
and Physics Department
Brown University
Providence, Rhode Island 02912

ABSTRACT

A single cell theory for the development of selectivity and ocular dominance in visual cortex has been generalized to incorporate more realistic neural networks that approximate the actual anatomy of small regions of cortex. In particular we have analyzed a network consisting of excitatory and inhibitory cells, both of which may receive information from LGN and then interact through cortico-cortical synapses in a mean field approximation. Our investigation of the evolution of a cell in this mean field network indicates that many of the results on existence and stability of fixed points that have been obtained previously in the single cell theory can be successfully generalized here. We can, in addition, make explicit further statements concerning the independent effects of excitatory and inhibitory neurons on selectivity and ocular dominance. For example, shutting off inhibitory cells lessens selectivity and alters ocular dominance, (masked synapses). These inhibitory cells may be selective but there is no theoretical necessity that they be so. Further the intracortical inhibitory synapses do not have to be very responsive to visual experience. Most of the learning process can occur among the excitatory LGN-cortical synapses. Some of these ideas are compared with experimental results.

*Present address: Nestor, Inc., 1 Richmond Square, Providence, Rhode Island, 02906.

STORING & RETRIEVING DATA IN A PARALLEL DISTRIBUTED MEMORY SYSTEM

ABSTRACT

TERRY WAYNE POTTER

B.S., Math, Kent State University, 1970
M.S., Computer Science, Rutgers University, 1972

The storage and retrieval of patterns in a Hopfield-like Parallel Distributed Memory is investigated experimentally with a view toward increasing its storage capacity.

The first two Chapters give an overview of *distributed memories* and in particular the Hopfield distributed memory. This is followed by a Chapter which experimentally identifies the basic storage capacity of the original Hopfield memory when using text patterns.

This *dissertation* then experimentally investigates new and untested methods to increase the storage capabilities of a Hopfield-like neural net. Increasing the storage capacity by using the continuous-valued Hopfield memory is explored in Chapter 3 and the impact on capacity of data representation is experimentally investigated in Chapter 4. We then focus on new ways of storing data (changing the interconnect *strengths*) including in Chapter 7 developing a new method called Modifying the Energy Contour or *MEC*. In addition, this Chapter also outlines how to increase error-tolerance through the use of noisy patterns.

The Hopfield distributed memory is then contrasted to another intelligent memory subsystem based on more of a traditional computer technology. In Chapter 8 we see that traditional computer technology using data-parallel techniques has a greater storage efficiency than possible with current Hopfield-like distributed memories. The design of this data-parallel memory is based in part on what is learned experimentally from the preceding Chapters on the Hopfield-like distributed mem-

ory. This fast data-parallel approach also supports retrieval of data patterns with noisy inputs although it does not have all the functionality of the Hopfield-like distributed memory.

The Hopfield Model and Beyond

Abstract

The standard Hopfield model (both digital and analog)
and algorithms to improve its performance are reviewed.
An analysis of the model and the modification algorithms
is given.   Future directions for continuous models which
have both large capacity and good error-correcting capa-
bilities are examined.

A Relaxation Model for Memory with High Storage Density

Charles M. Bachmann*†, Leon N. Cooper*†, Amir Dembo‡,
and Ofer Zeitouni‡

*Department of Physics and of ‡ Applied Mathematics
and † Center for Neural Science
Brown University
Providence, Rhode Island 02912

Abstract

We present a relaxation model based on an N-dimensional Coulomb poten-
tial. The model has essentially infinite storage capacity and, in addition,
well-defined basins of attraction about stored memory states. The model
is compared with the Hopfield relaxation model.

GENERAL POTENTIAL SURFACES AND NEURAL NETWORKS

Amir Dembo and Ofer Zeitouni

Division of Applied Mathematics
Brown University
Providence, Rhode Island 02912

ABSTRACT

Investigating Hopfield's model of associative memory implementation by a neural network, led to a generalized potential system with a much superior performance as an associative memory. In particular, there are no spourious memories, and any set of desired points can be stored, with unlimited capacity (in the continuous time and real space version of the model). There are no limit cycles in this system, and the size of all basins of attraction can reach up to half the distance between the stored points, by proper choice of the design parameters.

A discrete time version with its state space being the unit hypercube is also derived, and admits superior properties compared to the corresponding Hopfield network. In particular the capacity of any system of N neurons, with a fixed desired size of basins of attractions, is exponentially growing with N and is asymptotically optimal in the information theory sense. The computational complexity of this model is slightly larger than that of the Hopfield memory, but of the same order.

The results are derived under an axiomatic approach which determines the desired properties and shows that the above mentioned model is the only one to achieve them.

Analysis of Immune System Retrovirus Equations

(human immunodeficiency virus / acquired immunodeficiency syndrome)

Nathan Intrator
Gregory P Deocampo
Leon N Cooper

Center for Neural Science, Department of Physics,

and Division of Applied Mathematics

Brown University,

Providence, RI 02912

Abstract

An attempt has been made to mathematically model the patterns of viral growth and the associated immune system response characteristically associated with infection by the human immunodeficiency virus (HIV). By employing a very simple model of viral growth and the humoral immune system response, the interaction between a 'normal' virus and the immune system response is compared with that of a viral entity called an immune system retrovirus (ISRV) (Cooper, 1986). Some of the consequences of the model are presented in numerical simulations and compared to other models treating the cellular response of the immune system.

Generalization and the Backward Propagation Neural Network

by Charles M. Bachmann
Department of Physics and
Center for Neural Science,
Brown University,
Providence, R. I. 02912

ABSTRACT

Results of simulations in discrete and continuous input
simulations are discussed for the Rumelhart's Backward
Propagation of Error Neural Network. Comparison of. the
results offers a way to understand the problem of generalization
from a partial set of data in the Backward Propagation Network

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